F4?-: TS paper 4/26 Semifinal Draft (Some red-lines not on DISK)

Imaging Spectrometry-Concepts and System Tradeoffs

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ABSTRACT:

1 he concept of imaging spectrometry is finding broad application in scientific instrumentation for earth-based, airborne, and space applications. An imaging spectrometer is characterized by the combination of imaging with complete sampling in the spectral domain. In so doing, material identification can be accomplished and displayed in conjunction with the conventional recognizable image.

An imaging spectrometer incorporates a wide variety of technologies, including focal plane arrays, imaging and spectrometer optics, and spectral dispersing devices. 1 he design of a successful system involvos a complex set of tradeoffs incorporating the properites and limitations of the various technologies. For applications in the infrared, additional technologies such as focal plane cooling are required, and the other technologies present more limitations and constraints.

1 his paper will describe the system design process for a typical application, and will discuss the system performance parameters and tradeoffs, including choice of system architecture, signal to noise ratio, system resolution, spectral performance, calibration, anti the effect of artifacts such as detector non-u nifor"mity.

Introduction:

Over the past decade, the imaging spectrometer has become established as a powerful tool for a variety of measurement applications.[1,2,3] The central feature of typical designs is the complete, contiguous, coverage of a specified spectral region with sampling sufficient to resolve spectral features of interest. 1 he fundamental approach typically results in a generalized, multipurpose, design in which the number of spectral channels exceeds that dictated by any one application, but achieves an efficient realization of a broad suite of applications. 1 his generalized approach, while resulting in a large system data volume, provides enormous flexibility in the application and utilization of the data products, and allows experiments to be performed which were not visualized at the time that the instrument was designed.

An imaging spectrometer is fundamentally an imaging system in which a third axis of information has been added in the spectral domain. Where the human eye operates with three wavelength (color) sensors, the typical imaging spectrometer may have in excess of two hundred. The three-dimensional nature of the data has led to the term "data cube" to describe the data set which is generated. Before describing the physical implementation of an imaging spectrometer, it is useful to consider the functionality in terms of the data cube concept. While the ideal implementation would be one in which every element of the cube is acquired simultaneously, there is no practical way to do so. (This can be seen intuitively by recognizing that simultaneous acquistion of a conventional two-dimensional image requires a two dimensional detector array, whereas simultaneous acquisition of a data cube would require a three-dimensional device!). [-ailing to provide simultaneous acquisition is not a problem, provided that all elements of the cube can at least be spatially registered. I or example, every spectral channel for a specific point in the spatial plane of the data cube should correspond to the same location in the object or source. 1 his can be accomplished in applications with a moving platform through either push broom or scanning imaging implementations, and for stationary platforms, by acquiring a series of two dimensional images in different wavelengths. Many practical implementations do not, however, accomplish this, anti some allowance must be made in the subsequent processing in an attempt to simulate a fully registered data set.

1 he data cube construct also comes into play when considering how to store the data for later processing. Depending on the processing algorithms which are to be applied, it may be far more efficient to chose a particular format for storing the data.

While early imaging spectrometers were often limited by available technology, the state of the art has now matured to the point where, for many applications, the imaging spectrometer can be considered to be the architecture of choice. 1 wo enabling technologies are particularly significant: focal plane arrrays, and data processing. As will be discussed later, there have been tremendous advances in focal plane array technology since the first imaging spectrometers were designed. 1 his is particularly true for the infrared wavelengths where many of the scientifically important spectral signatures are located. One of the very first imaging spectrometer designs, the Airborne Imaging Spectrometer (AIS)[4] depended on a 32 x 32 IR array, which limited the instrument to 3? spatial samples (in one axis of the image) and 32 simultaneous spectral samples. Additional spectral coverage was provided by stepping the grating through 4 positions to provide a total of 128 spectral samples. In the ten years since that instrument was built, the technology has matured to the point where array sizes of ?56 x 256 are routine and up to 10?4 x 10?4 are under study.

In the data processing arena, there has been major progress in at least two important areas: processing speed, and the development of efficient algorithms for information extraction. '1 he latter is particularly important for applications where system constraints preclude returning all of the raw data produced by the instrument. The ability to return information rather than data will enable exciting new remote sensing missions which would not have been possible just a few years ago.

Definition of Requirements

1 wo sets of requirements or constraints are needed before instrument definition can proceed. The first set is the science requirements, which are developed by the scientists involved in a particular investigation. '1 he minimum set of science requirements is listed in 1 able 1.

'1 ABLE 1: SCIENCE REQUIREMENTS

Requirement	Definition
Field-of-View (FOV)	Angular measure of the area in which an optical system can image a target. Also defined in terms of swath width on the ground.
Spatial Resolution (IFOV or Sample Interval)	Angular subtense of one detector pixel. Also given as an equivalent area on the ground.
Spectral Range	The range of pertinent wavelengths.
Spectral Resolution (Bandwidth or Sample Interval)	'1 he subset of wavelengths, within the spectral range, which are imaged within one detector pixel.
Figure-of-Merit	Single value indicator of overall system performance. Examples, Signal-to-Noise Ratio, Feature-to-Noise Ratio, Noise Equivalent Change in Radiance (NEDL), Noise Equivalent Change in Reflectance (NEDr), Noise Equivalent Change in Temperature (NEDT).
Radiometric Calibration	Calibration of the absolute or relative system response to radiance or equivalent reflectance.
Spectral Calibration	Calibration of the system response to wavelength.
Geometric: Calibration	Calibration-t of the geometric imaging capability or quality of the system.

1 he science requirements define the basic system capabilities, however, to design a system, the mission requirements or constraints are also needed, Table ? lists the minimum mission constraints needed to specify an imaging spectrometer system.

TABLE 2: MISSION CONSTRAINTS

Constraint	Definition
Altitude	The height above ground level at which the system will operate.
Ground Velocity	The apparent speed of the system with respect to the ground.
Stability or Pointing	The deviation of the actual ground track from the ideal ground track, usually defined in 3-axes--pitch, roll, and yaw.
Orbit Offset	The average orbit to orbit separation of equatorial, orbital ground tracks .
Orbit Inclination	The maximum latitudinal extent of the ground tracks.
Mass	Mass allocated to the system.
Power	Average and peak power allocated to the system.
Data Rate	Data Rate allocated to the system. This parameter does not necessarily match the rate at which the system generates data.

Given both the science requirements and mission constraints, a set of instrument parameters can be developed. Self consistent sets of these instrument parameters are developed and traded against one another to meet the science requirements and mission constraints. Table 3 lists the first order instrument parameters.

TABLE 3: INSTRUMENT PARAMETERS

Parameter	Related Requirements
Étendue or $A\Omega$	IFOV, Spectral Resolution, Figure-of-Merit
Focal Length	IFOV, altitude,
Aperture	Figure-of-Merit, FOV
Focal Ratio or F-number	Figure-of-Merit, FOV
Pixel Pitch	IFOV, Spectral Resolution
Focal Plane Format	FOV
Integration Time	IFOV, Ground Velocity
Spectral Discrimination	Spectral Range, Spectral Resolution
Encoding Level	Figure-of-Merit
Mass	Mass Allocation
Power	Power Allocation
Data Rate	Data Rate Allocation

Architectures and Tradeoffs

Before the instrument parameters can be developed, the system architecture or design approach must be chosen. Imaging spectrometer data is expressed as a 3 dimensional array (2-D spatial by 1 -D spectral). Simultaneous acquisition of all three dimensions of the image cube would require a 3 dimensional array of detectors! Instead, time is used to multiplex one or two of the three dimensions. Imaging spectrometers can be classified by the way which this multiplexing is accomplished. The three general classes of imaging spectrometers are Whiskbroom (scanning), Pushbroom, and Framing (time-sequential staring).

In the whiskbroom system, a single-pixel field stop is scanned to produce one axis of the image. The other axis of the image is created by either moving the system downtrack and scanning another line or by stepping the single pixel field stop in the orthogonal direction to the “line scan” and then taking another line of data. The spectral information is created by spectrally dispersing the single pixel field onto a line array detector. Figure 1 shows a whiskbroorn system schematic wherein the second image axis is created by moving the system downtrack. Data produced by such a system is naturally generated in a band interleaved by pixel (BIP) format. The Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) is a an example of this approach. [5]

AVIRIS uses 4 grating spectrometers to disperse the spectral bands across the linear array.

In the pushbroom system, a slit field stop is used to simultaneously create one axis of an image. That is, the slit is imaged along one direction of an area array detector. The spectrum of each pixel in the slit is dispersed along the second dimension of the detector. Once again, the second axis of the image is created by the movement of the platform or by stepping the slit field stop in the orthogonal direction. Figure 2 shows a traditional pushbroom spectrometer system. Data is typically produced in band interleaved by line (BIL) format or BIP format. The Airborne Imaging Spectrometer (AIS) and the Hyperspectral Digital Image Collection Experiment (HYDICE) are exampes of this approach, using a spectrometer to image a slit field stop through a grating or a prism, respectively.

Another type imaging spectrometer architecture is the interferometric pushbroom system. Here, a series of interferograms are imaged in the "spectral direction". These interferograms are fourier transformed to retrieve the spectral scene information. Figure 3 presents an interferometric imaging pushbroom spectrometer system. In the framing, or time-sequential staring, approach a series of monochromatic two-dimensional images are acquired while stepping or scanning a spectral selection device. That is, the images are collected in a frame format on an area array detector and the spectral information is collected time-sequentially. The spectral selection device could be a filter wheel, or a tunable filter, or a spatially variable filter. Figure 4 shows a time-sequential imaging spectrometer implementation. The most straightforward example of this approach is the Voyager camera which uses a filter wheel. More exotic are Acousto-Optical and Liquid Crystal tunable filters (AOTF, LCTF) which allow much faster spectral tuning speed and random access to wavelength.

Within the whiskbroom and traditional pushbroom architectures a choice must be made between two spectral discrimination alternatives--gratings or prisms. Gratings offer the advantage of linear dispersion and broad spectral range, but often at the cost of throughput, and order overlap problems. Gratings may also carry optical power, thereby simplifying the overall optical design. Prisms offer high throughput and no order overlap, but at the cost of nonlinear dispersion and relatively high mass. The nonlinear dispersion can be partially compensated by implementing multi-element prisms, but at the cost of additional mass.

Table 4 lists the major tradeoffs between the four imaging spectrometer architectures. For each imaging spectrometer application, the attributes of each architecture are traded against one another to arrive at the optimal system design. For example, for the AVIRIS system, which flies aboard an ER-2 aircraft., the low altitude, wide FOV requirement, and relatively slow speed convolve into a whiskbroom imaging spectrometer optimally satisfying the science requirements and mission constraints. However, given the same basic set of science requirements, but changing the mission constraints to an orbital platform, pushes the optimal architecture approach to either a traditional or interferometric imaging spectrometer. The high spatial and spectral resolution coupled with the orbital velocity, does not allow enough integration time for either whiskbroom or most time-sequential staring systems to be practical.

Spectral Discrimination

Independent of system architecture it is useful to consider the various wavelenght selection techniques which are available. Narrowband spectral information is extracted from broadband light by a number of different filtering processes. A simple color filter works by absorbing all but a range of wavelengths. An interference filter tends to reflect all but a narrow spectral, reflecting and absorbing the rest of the spectrum. Sensors that use simple filters placed in a wheel such as the voyager cameras are usually not called imaging spectrometers because of the limited number of bands are limited by the size of the filter wheel mechanism and the time required to step to different filter wheel positions.

l-unable optical filters are being developed that can be considered as solid state filter wheels. Tuning time is much faster than mechanical filter wheels and the filters are typically random acces devices. Examples include the acousto-optical tunable filter (AOTF) and the liquid crystal tunable filter (LCTF). The AOTF works by inducing a volume diffraction grating in a crystal using an RF generator. The LCTF uses tunable birefringence in a polarization interference, such as a L yot filter. Optical systems can image through both devices and so TOFs are used in the framing camera mode.

Wedge filters are spatially varying interference filters. T hey exhibit a continuously varying passband over one spatial dimension of the filter. Bandwidth is typically a few percent of center wavelength. A number of imaging spectrometer designs use the wedge filter concept. Since the bandwidth of interference filters is a function of f/number, spectral resolution is compromised in fast optical systems. Filter defocus also limits spectral resolution, especially in the case where the filter is held in close contact to the detector array.

Dispersive spectrometers image a slit through a refractive clement such as a prism. '1 he slit limits the spatial extent of the broad-band source while the spectrometer reimages the slit through a prism. '1 he prism spectrally sorts the broadband light of the slit because the index of refraction and hence refraction angle is proporational to wavelength. Multi-element prisms are designed to increase the linearity of the dispersion. Imaging is restricted to the one dimension along the slit. Interesting trade-offs between instantaneous field-of-view, spectral resolution, and etendu drive the selection of optimum slit width. The length of the slit, anti correspondingly, the instanteous cross-track field-of-view is typically limited by the a phenomena known as spectral smile which is a variation in dispersive power across the cross-track field-of view.

Diffractive spectrometers are similar to prism spectrometers although they use a diffraction grating to spectrally sort the light. T he angle of diffraction off the grating is a linear function of the wavelength of the light. t lence, grating spectrometers are inherently linear with wavelength. 1 here is, however, an ambiguity between higher multiples of wavelength. This is usually solved by limited the spectral range of light to one octave, (i.e. the longest wavelength of light measured in the spectrometer is less than twice the shortest wavelength.) and using an order broad-band order sorting filter. T he spectral smile phenomena is also present in grating spectrometers.

limiting

Fourier transform spectrometers measure the spectral content of light indirectly, by measuring the periodicity of interference fringes. The fringes are sampled temporally or spatially. An example of the first case is the Michaelson interferometer which divides and then recombines a broad-band wavefront by using a beam splitter and mirrors. By changing the optical path length of one of the divided legs, a tunable wavelength phase error is induced. The recombined image interferes constructively or destructively depending on the phase of the error. As the optical path length difference is scanned in time, a detector in the image plane samples the interferogram. The spectrum is then re-transformed using a computer algorithm.

A fringe pattern can also be sampled spatially. Two coherent point sources will interfere to create a spatial fringe pattern. The spectral energy distribution of the point sources is obtained by the spatial Fourier transform of the fringe pattern. A device called a spatially modulated imaging Fourier transform spectrometer (SMIFTS) uses cylindrical mirrors to distribute a spatial interferogram along one access of a 2-D array, and cross-track image information across the perpendicular dimension.

Both types of Fourier transform devices require extremely linear detector response to ensure an undistorted spectrum. Spectral resolving power is limited by the extent of sampling of the shortest wavelength fringe pattern. Detector arrays are limited to less than a few thousand elements for the visible and a few hundred for the infrared wavelengths. This limits the spectral dynamic range of SMIFTS devices. Much higher spectral resolution can be obtained with Michelson interferometers, but at the loss of spatial field-of-view.

Focal Plane technology

The focal plane array (FPA) is the heart of an imaging spectrometer. In most cases the FPA determines the spectral and spatial coverage of the instrument, the ultimate signal to noise ratio, and the operational procedures of the spectrometer. In an ideal situation, the focal plane (detector and readout circuitry) can be designed to meet the instrument specifications. In ~~most~~ cases, however, existing focal planes are shoe-horned into the design and the instrument performance is compromised. A thorough knowlegde of the

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tradeoffs being made in the focal plane is important to guide the instrument design, to permit the closest fit to the mission goals.

Some specific tradeoffs that must be considered early in the design include 1) array format: Is a line array or an area array needed, and how many pixels does it take to meet the desired spatial and spectral resolution. More pixels are usually desired, but cost, availability, and data rate can limit the number of pixels a system can handle. 2) pixel size: A traditional rule of thumb is that the pixel size should be as small as possible, consistent with an acheivable focal ratio. To achieve a large system etendue requires large pixels (e.g. AVIRIS pixels are 200x200 urn with a focal ratio of approximately f/1) while technology limitations, in area arrays in particular, demand smaller pixels as the number of pixels increases. A balance between these two opposing trends must be found. 3) raising performance specifications such as linearity, dynamic range, and uniformity requires complex unit cell roadout circuitry, conflicting with required smaller unit cells in area arrays, and cost considerations. 4) operating temperature - FPAs, especially infrared arrays require cooling. In general, the lower the temperature the higher the performance of the array. Temperatures as low as 10K may be necessary. The need for a cooling system impacts the complexity, operability, and reliability of the imaging spectrometer. At the end of these trade studies for the FPA, the entire instrument design and performance will likely be determined.

Formats:

The design choice between a line array and an area array should be based on fulfilling the science goals of the instrument. All too frequently, however, the choice for an area array is based on the mistaken conception that it represents a higher, better, solution. An instrument designer should examine the particular strengths of each detector format before deciding which FPA to build the instrument around.

A line array detector (1-dimensional) offers several advantages over staring area arrays. The first is cost; the yield on a 256x1 line array of MC1 diodes is much better than a 256x256 area array of equivalently sized detectors. A second advantage is that the silicon readout circuit unit cell size is not tied to tho detector size. This permits the use of larger transistors and more complex circuits in the unit cell, allowing the readout to be optimized for low noise, dynamic range, linearity, etc. larger detector pixels (>1 00x100 urn) are more easily accommodated in a line array, if called for by the optical design.

Staring arrays, while more costly, size constrained, and usually noiser than line arrays, permit two imaging spectrometer designs that line arrays cannot accommodate. First, a pushbroom imaging spectrometer demands an area array, conferring the benefits of longer integration time and much higher spatial fidelity. The spatial and spectral resolution is directly determined by the number of lines and columns in the array. The second spectrometer design requiring area arrays involves a time-sequential approach, where the target image is focussed on the staring array through a spectral filter such as a liquid crystal filter. In both cases, the demands on the area array are high: high optical throughput into a large number of pixels, while putting low noise unit cells into smaller dimensions. Calibration issues, discussed in the next section, are increased greatly in instruments with staring arrays.

The fundamental parameter governing selection of a focal plane is what wavelengths are to be detected by the array. For visible wavelengths (0.4 - 1.0 μm), the silicon charge-coupled device (CCD) is the detector of choice. The CCD represents a mature technology that has achieved impressive results. High quality arrays can be obtained from several vendors. High quantum efficiencies and low read noise (~ 1 electron) have been demonstrated in scientific-grade devices. Very large formats up to 4096 X 4096 have been fabricated and operated. A wide range of architectures are available; depending on the application, high frame rates, electronic shattering, multiple outputs, and frame transfer devices can be produced.

for the short (l-3 pm) and mid (3-5 μm) infrared, hybrid arrays consisting of a diode array iridium bump bonded to a silicon readout circuit represents the current state of the art. The two major detector materials are InSb and MCT. InSb arrays, which can respond to 5.5 μm, have been fabricated in formats up to 640x480; other InSb arrays have achieved extremely low noise levels (<1 O electrons) at reduced temperatures. MCT arrays have been fabricated in formats similar to those found in InSb. The cutoff wavelength of a MCT array can be specified; by utilizing an array whose response matches the instruments requirements, the operating temperature is maximized and the background flux minimized without the use of cold filters. The choice of silicon readout circuitry depends greatly on the operating conditions such as frame rate, noise levels, dynamic range, and linearity. In general, the readout and the detector array must be designed together as an integral system; FPAs utilizing mix and match components rarely give good performance and place more difficult demands on other parts of the instrument.

The availability of F"['As at longer wavelengths (> 8 microns) is more uncertain. MCT diode arrays up to 128x128 have been fabricated for the 8 - 11 pm range, but are designed only for high background environments. Work is continuing on improving the MCT material and extending the wavelength coverage out to 14 pm. Arrays with this range will likely be made available in the next five years. The alternative to MCT FPAs are Si :As impurity band conductor (IBC) detectors. IBC arrays offer wide wavelength coverage (5 -28 μm), good quantum efficiency (>50% in the 1 WIR), and come in formats up to 256x256. The uniformity of these arrays, being based on silicon epitaxy, is much better than LWIR MCT. The major disadvantage to these arrays is the operating temperature must be <12K; the necessary cryogenic engineering can be a significant expense.

Future trends:

For future imaging spectrometers, focal planes will likely incorporate several new features just now being developed. These FPA features all have as their goal the optimization of the instrument and not simply giving the highest D* obtainable. Other factors such as ease of operation, reduction in the number of arrays required, reduction in the instrument size, elimination of supporting circuitry, higher operaturing temperatures, and closer matching of FPA abilities to the instrument demands must be factored into the choice of future focal planes. Reduction in the cost of constructing and maintaining these instruments will be a major driver in the choice of the focal plane. These cost drivers, however, will demand *more* value be put into the focal plane, in much the same way as more sophisticated microprocessors have enabled smaller, cheaper computers.

One important trend is the design and use of custom readout circuits for the focal plane array. The advances in circuit modelling, the growing database of array unit cell designs, and the increasing availability of silicon foundries have reduced the cost of a complex hybrid readout circuit. Custom readouts offer several benefits to the instrument builder. Since each column in the array is assigned to a known spectral channel, each unit cell can be indivually optimized to the expected operating conditions: options such as differing pixel sizes or well depths can be easily defined. More advanced input circuits (charge transimpedence amplifiers, chopper stabilized amplifiers) are being developed that offer lower noise, improved linearity, and stabilized operating points, especially in low background environments. The inclusion of analog signal processing circuits, e.g. correlated sampling circuits and analog/digital converters, or clock drivers on chip can reduce noise, improve SNR, and simplify the interface to the associated electronics in the instrument.

A second trend likely to make an impact on future instrument designs is the integration of optical functions onto the focal plane. This is driven by the desire to cut down the optical elements, simplify the optics, and reduce the imstrument volume. One area of integration is in the spectral dispersion dimension of an imaging spectrometer. Spectral discrimination can now be accomplished with thin film filters applied to the front surface of arrays, in effect a linearly variable interference filter. Lithographically defined gratings and meshes will directly couple light into detector elements. Another area is in the collection of photons and matching the optical system to a small detector. Micromachining techniques, originally developed in silicon, have been used to fabricate microlens arrays, permitting smaller detectors to be used while maintaining the signal flux onto the detector. More advanced structures like micro cold shields, interferometers, and deformable mirrors are being conceived and tried today.

A final trend is the push toward higher operating temperature detectors. A reduction in the cooling requirements for a given level of performance in the array will greatly help imaging spectroemters in the mass, power, and volume needed. Advances in MCT material processing have permitted 5 micron arrays to operate at temperatures reached by thermoelectric coolers.[6] New work in InGaAs alloys has yielded high performance SWIR arrays capable of operating at room temperature.~ l-or longer wavelengths, arrays of thermal detectors (bolometers and pyroelectrics) are under development; while not matching MCT diodes, these devices can operate at much warmer temperatures if the D* requirements are not high (<10^{10}). Taken together, these new technologies will permit much smaller, more reliable and user friendly systems, all important goals if imaging spectrometers are to be accepted in commercial applications.

Calibration

Calibration of a imaging spectrometer consists of the quantification of the sensor's geometric, spectral and radiometric properties. l-he complete calibration process consists of (1) laboratory characterization, (2) laboratory calibration, (3) in-flight calibration validation, and (4) subsequent laboratory and in-flight measurements to verify the sensor's continued performance. Each of calibration attributes may have long term characteristics that change over time. Other sensor “features” interfere with straightforward application of calibration parameters. The degree that all of those effects can be corrected determines the ultimate accuracy of the calibrated sensor.

The geometric calibration of deals with the *imaging* aspects of an imaging spectrometer. Relative geometric calibration measures field-of-view (FOV), instantaneous field-of-view (IFOV), and spatial sampling interval. The IFOV is defined as the full width at half maximum of the spatial response, function of a specific spatial element. The spatial response function is measured by angularly scanning a point target across the field of view of a spatial element. 1 he IFOV is measured typically measured in milliradians. 1 he IFOV is likely to be different in the down-track direction and cross-track directions. It will vary across the field-of-view in all but the whiskbroom scanner type of imaging spectrometer. The spatial sampling interval (SS1) is the angular spacing between two adjacent spatial elements. There is much debate over whether to employ critical sampling, whore the IFOV matches the sampling interval, or Nyquist sampling, where the IFOV is twice the sampling interval. The trade-off exists between the requirement to eliminate aliasing of high spatial frequency target information versus the costs of dealing with a four times increase in data volume required to Nyquist sample. The IFOV is determined solely by the point spread function of the optical system and sampling is determined solely by detector pitch in both cases.

Absolute geometric calibration determines specific latitude and longitude coordinates for each image pixel. This requires absolute position knowledge, such as can be obtained using a ground positioning system (GPS), and absolute pointing, knowledge from the platform inertia navigation system (INS). If the observed terrain is not flat, then topographic information is also required. 1 his can be inferred from previously measured digital elevation models, from laser or radar altimeters, or from the imaging spectrometer data directly. The latter approach estimates the column abundance of a well mixed gas such as nitrogen, oxygen, or carbon dioxide by measuring the shape of an absorption feature of that gas.

Instrument features that effect geometric calibration include scan jitter, field of view distortion, and temperature varying defocus and magnification. Any uncorrected platform motion such as pitch, roll and yaw will also effect image fidelity and may interfere with spectral coregistratration. Real time correction of these motions such as roll correction in a whiskbroom scanner or a three axis gimbal help to reduce the magnitude of the pointing errors.

Spectral calibration measures the spectral response function of each of the imaging spectrometer spectral channels. The bandwidth is the full width at half maximum of the spectral response function. The centerwavelength is either the maximum, mean, or median wavelength of the spectral response function. 1 he best description depends on the application. The spectral sampling interval is the difference between centerwavelengths of two adjacent spectral channels.

Prism-based imaging spectrometers exhibit non-linear dispersion which in the absence of a match non-linear detector pitch results in bandwidth and spectral sampling interval varying as a function of wavelength. Interferometric systems are linear with wavenumber, not wavelength. Grating systems are best if a constant spectral sampling interval is desired but all systems are susceptible to bandwidth variations as a function of wavelength.

Calibration of the spectral channels is tied directly or indirectly to atomic 'emission line spectra. One method is to use the emission line source to calibrate a scanning monochromator, which is in turn used to spectrally scan a the sensor under calibration. This method is used to achieve spectral calibration accuracy of 0.2 nanometers absolute. Some pushbroom area array imaging spectrometers are calibrated by directly observing the emission line source, and curve fitting the center wavelength and bandwidth parameters by a-priori knowledge of the dispersion of the optical system. Interferometric systems are inherently well calibrated in the relative spectral domain. Some tunable filter based systems are calibrated by scanning the filter across a fixed source. In any of these methods, it is vital to illuminate the sensor in the same way that would be used during data acquisition. This means filling the full numerical aperture of the optical system and using the right set of conjugates when coupling the source to the sensor.

Inflight calibration of the spectral and radiometric characteristics of a imaging spectrometer is also inferred by the depth and position of atmospheric absorption lines. A technique has been developed by Green to vary center wavelength position and bandwidth as applied to an atmospheric radiance model and comparing the results with calibrated sensor retrieved radiance. 1 his technique also implies a-priori knowledge of sensor spectral characteristics.[8]

Radiometric calibration of an imaging spectrometer measures the instrument response to spectral radiance. Radiance is defined as the photon flux per area per solid angle per spectral bandwidth as is often measured in units of microwatts per centimeter squared per steradian per nanometer. I-he instrument response is the relationship between input radiance and output digitized signal for each unique spectral-spatial element of the sensor.

As with geometric and spectral calibration, radiorneteric calibration can be defined in terms of a range, interval, and bandwidth parameter. '1 he range covers the minimum to maximum range of radiance levels that are measured without saturation. This is often based on the range of expected torrential radiance for lambertian targets or for a range of brightness temperatures for thermal systems. 1 he interval or sampling parameter corresponds to one over the number of analog to digital bits also known as the quantization level or radiometric precision. 1 he bandwidth parameter corresponds to the RMS noise of the system. 1 his parameter is often expressed in terms of noise equivalent radiance (NEDL) . In the absense of any system noise, a sensor will still be limited in performance by photon noise which increases as the square root of the signal level. Hence it is common for NEDL to be a function of radiance.

Response linearity is a highly valued instrument attribute because is simplifies the response relationship to a simple gain and offset term. Response linearity is an absolute requirement for interferometric systems in order to overcome the ambiguity caused by spectral response variations of the detector. A non-linear response may be approximated by some other relationship or by a look-up table with the calibration complexity proportional to the number of parameters required to accurately describe the relationship.

l-he spectral and radiometric response varys from element to element in the typical detector array. From this fact, one can conclude that the complexity of the radiometric calibration is also proportional to the number of detector elements used. Whiskbroom-line array scanners require a minimum of one radiometric response function for each of the spectral channels. Pushbroom area array scanners require a separate calibration for each spectral-crosstrack element. An exception to this rule is the tunable filter framing camera imaging spectrometer which requires a separate calibration for each spectral band used for each element of the detector array. F"or the case of a linear response imaging spectrometer that produces an image cube with dimensions 200 spectral by 500 by 500 spatial elements, this corresponds to 400 calibration parameters for the whiskbroom, 200,000 for the pushbroom, anti 100,000,000 for the framing camera!

Other instrument parameters will also impact the complexity of imaging spectrometer calibration. For example, if the instrument response varys as a function of instrument temperature, then all of the above calibration parameters will require an additional temperature dimension. But if the change in response as a function of temperature also shows a hysteresis effect, then the current temperature and all previous temperatures are calibration parameters. Such effects as this can quickly get out of hand and render calibration impossible. Other instrument features to avoid, if possible include fixed pattern noise, latent images, ghost images, spectral contamination, shifts in the spectral bandwidth or center wavelength, sensitivity to polarization, spectral spatial rnisregistration and lack of radiometric stability.

The absolute accuracy of radiometric calibration is tied to radiance standards constructed from a source of known irradiance and a target of known reflectance through a atmosphere of know transmission and scattering. In the laboratory, a NIST irradiance standard is typically used in conduction with a pressed halon or Spectralon reflectance target. For calibrating large field of view sensors, an integrating sphere is used as an intermediate transfer standard. Inflight calibrations *are* are also used of uniform ground targets. A radiative transfer code such as Lowtran or Modtran is input with time, date, latitude, longitude, optical depth, water vapor content, aerosol content and measured ground reflectance in order to predict the radiance level at the sensor. Agreement between the laboratory and inflight calibration techniques across the spectral range of the imaging spectrometer gives good confidence that the calibration is accurate.

The state of the art in radiometric calibration is 5% absolute for current whiskbroom imaging spectrometers.[9,10] Further improvements are likely in the areas of detector based calibration using quantum efficient detectors, direct solar irradiance response comparison and calibrations which account for spatial variations in atmospheric transmission and scatter. Spectral calibration certainty of 0.2 nanometers in bandwidth and center wavelength knowledge is also currently acheived in whiskbroom systems. Improvements in inflight spectral calibration sources will reduce this uncertainty further. Interferometic based imaging spectrometers are most likely to yield the highest spectral calibration accuracy. Absolute geometric calibration of imaging spectrometers is primative when compared to the accuracies acheived by photo-reconnaissance sensors. Improvements in differential GPS and better pointing stabilization platforms will help to improve this situation. Framing camera systems, being most like photo-reconnaissance systems are likely to lead in the area of absolute position accuracy.

Summary and Conclusions:

The imaging spectrometer has matured to the point where highly capable systems can be realized, covering a broad range of wavelengths in the visible and infrared. A specific design can draw on a wide variety of technologies in optics, spectral selection devices, and focal plane arrays, with the specific implementation tailored to the unique requirements and system constraints.

The successful deployment of imaging spectrometers in many applications will depend on reducing the size and mass, and on developing data handling methods to deal with the high data rates. Continuous technolgy improvements in the areas of focal planes, high-density electronics, innovative spectral selection approaches, and data processing technology will all enable powerful new implementations of this important instrument technology.

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...To be add supp

[4] <tbs--citation on Airborne Imaging Spectrometer (AIS)>

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Ref . 4

LaBaw, D., "Airborne Imaging Spectromete-: an advan ced concept instrument ", Proc of SPI E, vol 430 (1983)

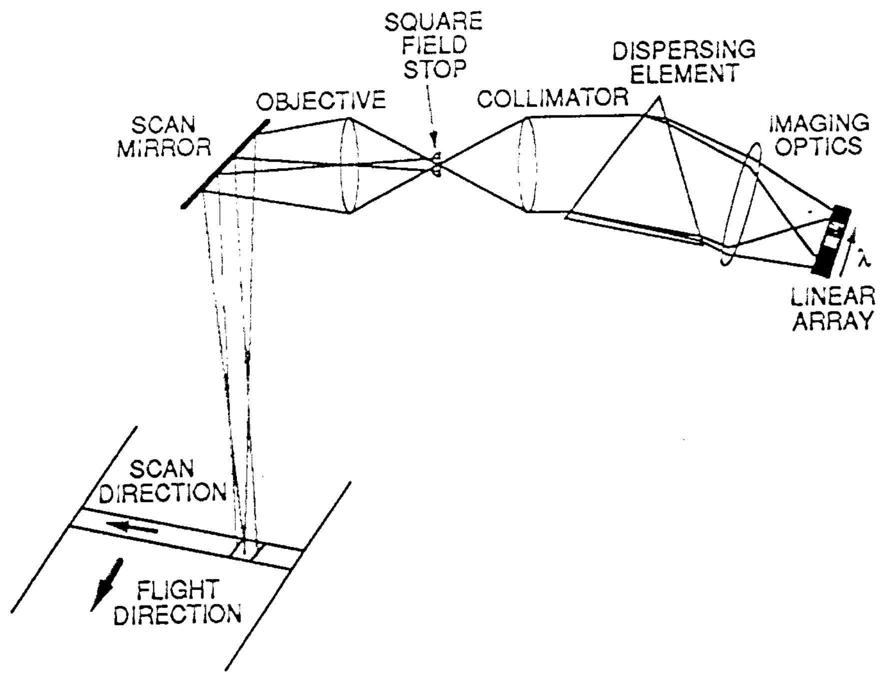
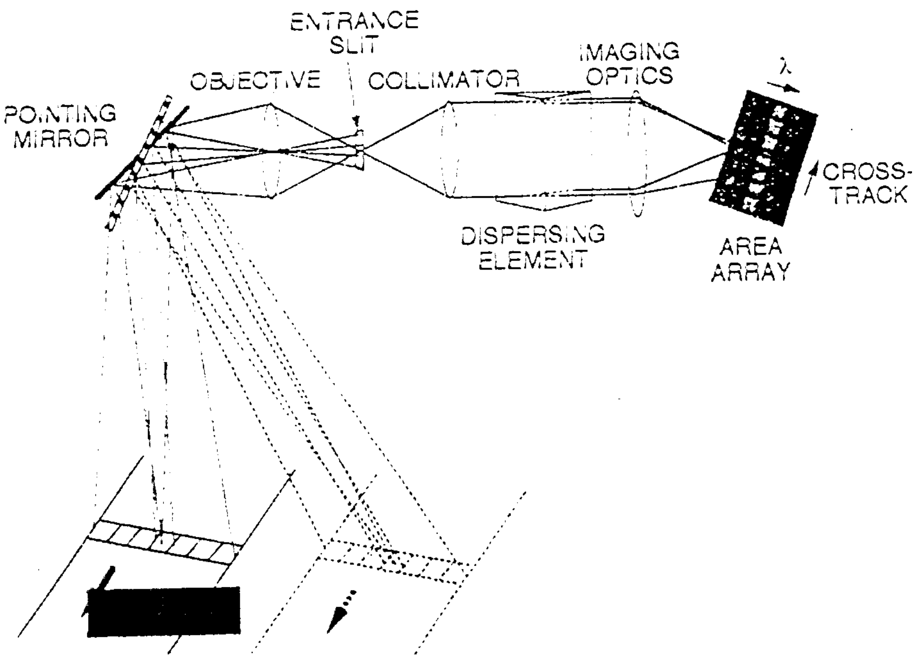


fig 1 ~~C.~~ WHISKBROOM IMAGING SPECTROMETRY WITH LINEAR ARRAY.

File: IS Types



~~D~~. POINTABLE PUSHBROOM IMAGING SPECTROMETRY WITH AREA ARRAY.

Fig 2

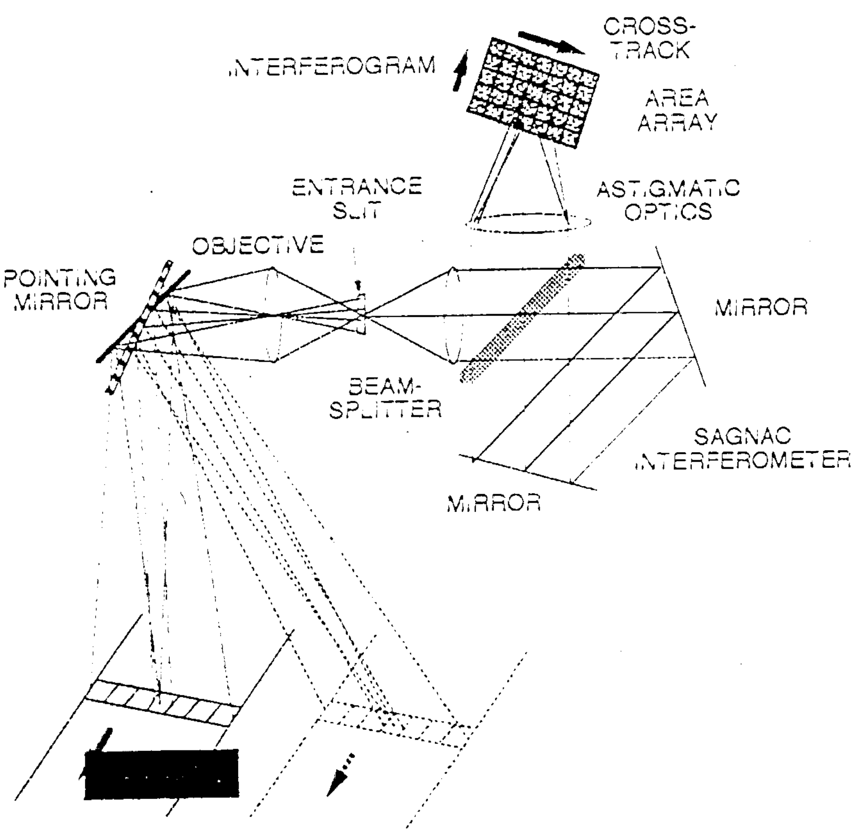


Fig 3 ~~F~~. POINTABLE PUSHBROOM IMAGING SPECTROMETRY WITH AREA ARRAY USING SPATIALLY MODULATED IMAGING FOURIER TRANSFORM SPECTROMETER (SMIFTS)

File : IS Types

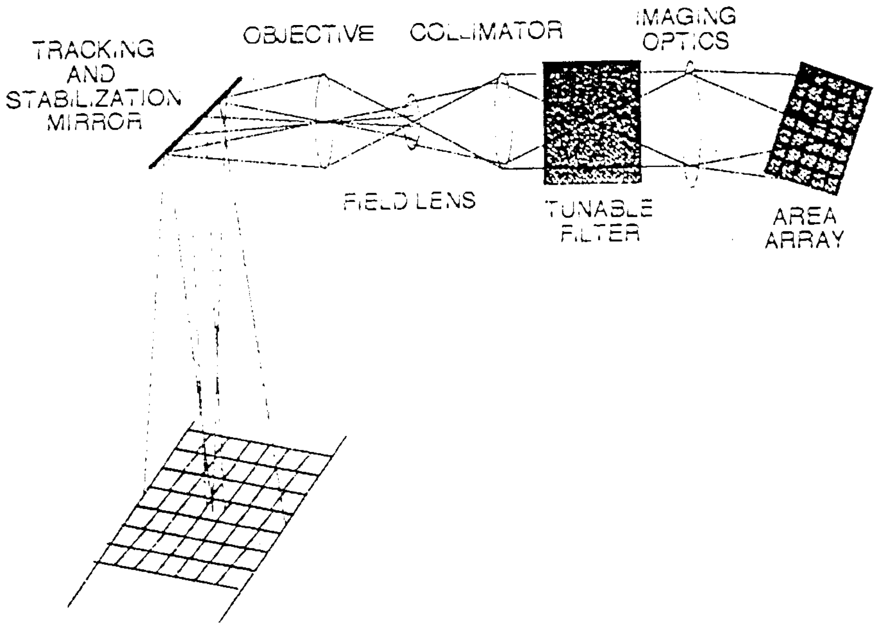


Fig 4 ~~E~~. TUNABLE FILTER MAGING SPECTROMETRY WITH AREA ARRAY

File: IR TIp20

Table 4 (No ...

JPL

MAJOR TRADEOFFS

APPROACH	PRO	CON
W S BROOM	SIMPLE, FAST, OPTICS SIMPLE FOCAL PLANE SIMPLER, BETTER, CALIBRATION WIDER FOV BACKGROUND CONTROL.	REQUIRES SCANNER FASTER ELECTRONICS PROCESSING FOR IMAGE RECONSTRUCTION
PUSHBROOM	NO MECHANISMS HIGHER PERFORMANCE (MULTIPLEX ADVANTAGE	MORE COMPLEX FOCAL PLANE LIMITED FOV MORE DIFFICULT CALIBRATION MORE COMPLEX OPTICS SPECTRAL "SMILE"
INTERFEROMETRIC	THROUGHPUT STRAY LIGHT REJECTION	POST-PROCESSING REQUIRED STRINGENT DETECTOR LINEARITY REQUIREMENT SPECKLE
TIME-SEQUENTIAL STARING	SIMPLE, COMPACT, SYSTEM (NO SPECTROMETER OPTICS) HIGH PERFORMANCE WITH SMALL OPTICS	ON MOVING PLATFORMS, SUCCESSIVE SPECTRAL SAMPLES NOT REGISTERED - RECONSTRUCTION DIFFICULT OR IMPOSSIBLE TUNABLE FILTER PARAMETERS MAY NOT FIT REQUIREMENTS